Resource History Matters: Resource System Path Dependence in the Anthropocene

(Working Paper)

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Abstract

Path dependence occurs when early decisions in an institution's or technology's history has irreversible implications on its future development and efficiency. The design of a machine or the interpretation of a law are both examples of processes of adoption and development where early events determined future outcomes for the subject's use and application. This paper argues that, like these examples, social-ecological systems (SES) also exhibit path dependence as system managers and appropriators alter system functions. Resource systems vulnerable to path dependence can experience significant and permanent changes in resource system functions as appropriator and manager decisions narrow the range of future options for resource system use. In defining resource system path dependence, this paper examines subtractability and the effects of resource system management on resource system attributes. The paper also refashions institutional analysis's conception of a resource's subtractability to distinguish between appropriable resource units between appropriators and the effects of appropriation on the resource system. With these elucidations, subtractability can address two issues; whether a resource unit can be fully appropriated at a moment in time and the ability of the resource system to continue to produce resource units across time. The human-ecology concept of resilience and adaptive cycles is also used to clarify the process of resource path dependence as a series of thresholds that, once crossed, cannot be feasibly reversed.

Introduction

Institutional analysts are increasingly aware of the role that governing institutions play in resource system collapse and are now focusing on creating solutions to these problems. Most proposed solutions seek to make governance and legislation more flexible and adaptable to changes in the resource, an approach called "adaptive governance and management" (Decaro, Chaffin, Schlager, Garmestani, & Ruhl, 2017; Folke et al., 2002, 2012). However, creating and assessing adaptive institutions examines only part of what is at play in resource system failure. Resource systems, such as fisheries, forests, and groundwater, i.e., natural resources subject to human use, are nested within social-ecological systems (SESs). SESs are connected institutional and ecological subsystems linked through mutual interaction between institutional actors and ecological functions (Gallopín, 2007). When a resource system fails, the relationship between it and the SES has also failed, for beneficiaries can no longer derive services through its use. To what extent can SESs adapt to new patterns of use? What is the institutional design process that leads SES beneficiaries to ensure that their systems outlive them and serve the next generation? Perhaps the most pressing question is this: how can SES beneficiaries and other interested groups act through governance structures to prevent resource system collapse due to increased variability in the ecosystem in which the resource is nested?

To answer these questions, institutional analysts need to examine the relationship governance has to resource system failure within SESs. Governing a resource requires that appropriators and managers are coordinated through varying institutional levels that prescribe, invoke, apply and enforce rules as well as develop social norms (Oakerson & Walker, 1997, p. 30; E Ostrom, 2005). In a SES, the resource system responds to changes in rules and norms through adjustments in appropriator and manager behavior, and its performance can give decision makers signals to alter resource conditions. However, the role of the resource in altering resource management strategies pursued by SES governance has not been thoroughly explored. This oversight is apparent in the context of resource attributes that are manipulated as part of management and appropriator activity and which also provide signals to institutional actors for future resource operations. These considerations apply to the effects of resource unit appropriation on resource system functions and how the resource system is structurally modified by managers. By understanding the dynamics between institutions and resource systems, analysis can begin to integrate resource system behavior into the institutional analysis of SESs.

The beneficiaries of an SES (appropriators, managers, or others) derive benefits from resource systems contained within the SES's ecosystem. Social-ecological systems contain multiple resource systems that each produce unique resource units for the SES's beneficiaries (Ostrom & Cox, 2010, p. 6). In this discussion, resource units are defined as the divisible portion individuals appropriate from the resource system, e.g., fish, water, grass, logs (E Ostrom, 1990). Some resource unit beneficiaries, here called *appropriators*, are individuals or organizations that withdraw resource units from a resource system. The *managers* of a resource system perform non-appropriative activities to maintain the functions of the resource system. Managers are not necessarily appropriators or other beneficiaries of the SES; they can instead be external entities that manage activity across the ecosystem's multiple resource systems from outside the institutional boundaries of the SES. Together, managers and appropriators are the institutional actors who govern a resource system. Governance in an SES provides system management by regulating appropriator activity using norms and rules and facilitating a resource system's renewal and maintenance, such as biological reproduction of animals and plants. Management activities also provide resource system functions, such as the controlled burn of a forest. Manager and appropriator activities can be pursued individualistically, such as in the case of resource unit appropriation, or by collective action organized through the governance structure. Each of these activities can be thought of as operations on the resource system that affect how the resource system functions.

SESs develop over time as manager and appropriator operations alter how the ecosystem's resource systems function (F Berkes, Folke, & Colding, 1998, p. 21). Shifts in a resource system's behavior are precipitated by changes in the *resource system's attributes*, the physical elements within a resource system that interact to produce a resource unit. Since attribute changes can affect how the resource system and the ecosystem functions, these events can determine how institutional actors approach their governance decisions concerning management and appropriation (Anderies, Janssen, & Ostrom, 2004). SESs that function poorly are characterized either by sub-optimal resource unit production, such as poor-quality wood and low crop yields. In some cases, the ecosystem can collapse due to deficient governance practices. Long-enduring SESs on the other hand display a dynamic relationship between institutional practices and resource systems to the point where they interlock to create mutual dependence (F Berkes et al., 1998, Chapter 1). Resource management and governance in these systems remains flexible as managers and appropriators pursue different objectives depending on the needs of beneficiaries and the ecosystem (Armitage, 2008, p. 16). Developing knowledge about the ecosystem's resource systems, creating institutional structures to adapt to changing conditions, and fostering SES absorption capabilities to internal and external shocks have all been attributed to enduring SESs (F Berkes et al., 1998, p. 21).

Previous Approaches to Resource System Change

Resilience

Among existing institutional analysis concepts, ecosystem resilience comes closest to describing long-term SES behavior patterns. Resilience in human ecology refers to the extent to which an ecosystem can absorb human impacts before the system shifts into an alternative state (C.S. Holling, 1973, p. 14). In resilience theory, ecosystems can have multiple equilibrium states. An ecosystem equilibrium occurs when its attributes maintain a constant relationship with each other within their resource systems while providing a respective resource unit or service (C. Holling, 1996). SESs with high ecological resilience will, in a disturbance event, maintain their attributes and processes that control system behavior. Systems with low resilience, in contrast, will experience a change in attributes and processes as a result of the event (Folke et al., 2012, p. 567). Resilience increases with greater diversity of key structuring attributes that drive resource system processes (C.S. Holling, 1973; B. H. Walker, 1992). SES beneficiaries can create institutions that affect their ecosystem's behavior by managing attributes, either altering or eliminating them (Folke et al., 2002). These operations in effect manage an ecosystems resilience.

When SES manager and appropriator operations are successful, their actions keep the ecosystem and resource systems from moving into a different or sub-optimal stable state (Fikret Berkes, 2009, p. 1693). Resilience theory has developed tools to explain long-term SES behavior based on management actions, most importantly the adaptive cycle model. An adaptive cycle is an infinite loop of resource system phases of exploitation, conservation, destruction and renewal (Holling, 1986, p. 95). In Holling's adaptive cycle model, "how long an inappropriate policy is successful depends on how slowly the ecosystem evolves to the point when the increasing fragility is perceived as a surprise and potential crisis." (C S Holling, Allen, & Gunderson, 2009, p. 102). Different points in the cycle correspond to varying degrees of resilience. The resilience of a resource system is expected to decrease from exploitation to conservation and increase from creative destruction to renewal (Gunderson & Holling, 2001, pp. 6–8). Separate adaptive cycle models can be interlinked to demonstrate system processes occurring at different temporal and spatial scales, with faster adaptive cycles occurring at smaller scales and slower cycles taking place at larger scales. The total interlinked system is called a "panarchy" and can explain patterns of resource renewal and collapse by referring to processes occurring at different scales (Gunderson & Holling, 2001). Resource managers and appropriators develop knowledge about the overall system through interacting with it, and create institutions and management strategies according to the placement of the process in the panarchic scale (F Berkes et al., 1998, p. 19). An adaptive cycle therefore demonstrates that a well-functioning SESs reflects the mutual adaptation of institutions and the resource system to balance the preservation of functions with requirements for stability. The model of an adaptive cycle can then demonstrate the mechanisms for ecological and institutional adaptation at multiple levels of time and space.

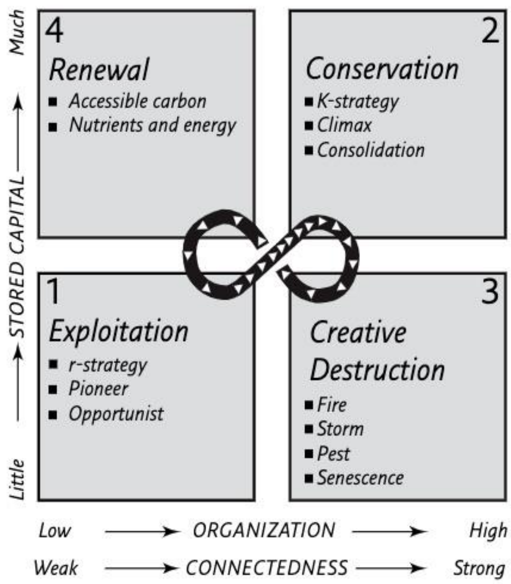

Fig. (1) The Adaptive Cycle. From Holling, C.S, (1986) The Resilience of Terrestrial Ecosystems: Local Surprise and Global Change, Sustainable Development of the Biosphere, Clark WC, Munn RE (eds). Cambridge University Press, Cambridge, UK

In comparison to institutional analysis, a panarchy can present a SES model where historical effects on a resource system are connected to current operations. However, the panarchy model itself cannot be straightforwardly integrated into the current understanding of institutions. The concept is inhibited by its vagueness, and while this makes it useful for its application to multiple circumstances, there is no agreed upon analytical method. An analyst looking at a SES may be able to identify how certain institutional events fit into an adaptive cycle. However, it will be very difficult to find the corresponding panarchic level it fits into, or its placement in overall resource history. Specificity is important to consider since analysts can then describe the integration of manager and appropriator operations into resource system processes.

Institutional Analysis

A similar critique can be applied to institutional analysis. Most often, when an analyst approaches a SES, they describe it in terms of the action arenas occupied by different actors and the rules that enable or constrain their actions (E Ostrom, 2005). Resource units and attributes are excluded from the analyst's field of vision, and for the most part is assumed to exist outside of the arena until drawn in by actors. However, this model is clearly not the case, as is seen in adaptive management practices where managers and appropriators react to resource system behavior (Folke et al., 2012, p. 559; Walters, 1986). In these cases, resource system attributes are better thought of as actors within the action arena, acting and reacting under certain rules of interaction. This paper is not proposing that ecosystems can be analyzed through institutional analysis; ecosystems operate under uncertainty and follow different patterns of interaction. However, it may be useful to consider certain action arenas as being an institutional-ecosystem nexus. In these cases, the reaction of an attribute or their lack of presence within an arena may be as important as those actions taken by actors. Taking this approach may allow analysts to think of institutions as being more dynamic than static.

The tendency in institutional analysis the adaptive cycle model to keep ecology and institutions distinct from each other gets to a wider point on examining SES governance. As a result of keeping them separate, analysts can be left with a gap of understanding between how the resource system affects institutions and vice versa. To create a cohesive vision of a SES, resource attributes need to be thought of as playing specific roles in governance, as well as working together within the ecosystem's resource systems. Since the diversity and characteristics of attributes determines the range of options that can be pursued by managers, losses in attributes need to be explained in terms of manager and appropriator activity. Therefore, it will take a deeper elaboration of the adaptive cycle model and principles in institutional analysis to be able to examine the effect that historical factors have on current resource system use.

Path dependence may offer a framework to understand these gaps left by the focus on resilience and adaptive cycles. Path dependence has been traditionally defined as the long-term effects that decisions have on the future development and efficiency of institutions and technologies (Liebowitz & Margolis, 1995)—in short, how past decisions constrain future decisions. Path dependence, I will argue, should factor into the analysis of SESs. Since the evolutionary path of governance and management is important to understanding a political system's current constraints, it is natural that analysts would want to examine how past resource system decisions decide current and future operations (Pierson, 2000, p. 251). I expect resource system path dependence to occur when alterations to a resource system's characteristics through governance and management practices restrict its ability to respond to disruptions or new patterns of use.

Scope of Path-Dependence Analysis

Path dependence is a notoriously "blurry" concept that, while being recognized by researchers as being vital to understanding institutional development, does not have an established empirical basis (Vergne & Durand, 2010, p. 737). It thus remains outside the scope of this paper to make a claim about a methodology for testing path dependent behavior. Instead, the aim is to explore avenues for the development of a path dependence analysis that is SES-focused by using widely reviewed case studies in the academic literature.[1]

Path dependence is understood here to be a decreasing scope of action due to positive feedbacks and self-reinforcing dynamics (David, 2007, p. 1; Schreyögg & Sydow, 2011, p. 323). Path dependence becomes a concern when a systems begin to produce or prefer sub-optimal resource outcomes in terms of quantity or quality, or in extreme cases, stop being productive entirely (Arthur, 1989, p. 116). *Resource system path dependence* occurs when a resource system cannot produce desired resource units as a result of historical patterns of use. Some common-pool resources (CPRs) are uniquely vulnerable to resource system path dependence as resource attributes are altered or eliminated through manager and appropriator operations. CPR's are defined as resources that exhibit high subtractability and low excludability (E Ostrom, 1990, pp. 31–32). When CPRs exhibit path dependence, resource units are vulnerable not only at a point in time but also across time as various types of appropriator and manager decisions impact future uses of the resource. In these cases, "marginal adjustments of individual agents may not offer the assurance of optimization or the revision of sub-optimal outcomes" over time, meeting the criteria for path dependent behavior (Liebowitz & Molinga, 1995, p. 206). To analyze resource system path dependence, the necessary conditions for resource system renewal need to be examined in terms of the relationship between the resource unit and resource system. Since Holling's adaptive cycle model (Gunderson & Holling, 2001; C. S. Holling, 2001) is well suited to mapping the progress of a single resource system from renewal to collapse in respect to attribute diversity, it will be the primary way that resource path dependence is formulated here.

Defining Excludability and Subtractability

Traditional Perspective

Two descriptive categories are useful for assessing CPRs: excludability and subtractability (E Ostrom, 1990, pp. 31–32). Excludability refers to the degree to which appropriators can be excluded from accessing the resource system (1990, p. 32). Resource systems with high excludability have physical features that can be used to limit the number of appropriators, such as a fenced-in grazing land or a small pond that can be easily enclosed by private property. Resource systems with low excludability lack such features, such as unfenced pasture or a large lake. Subtractability has been traditionally defined as the degree to which a resource unit is fully appropriated by an appropriator (E Ostrom, 1990, p. 31). In cases of high subtractability, multiple appropriators cannot use the same resource unit. In cases of low subtractability, the appropriators can jointly use a unit. For example, resource units with high subtractability, such as water in a lake or grass on a savannah, can only be used by a single appropriator, while resource units such as roads and radio airwaves are not reduced by individual consumption and can be shared by multiple appropriators. Resources are considered renewable in terms of the rate of replenishment of the resource unit stock in the resource system as compared to the flow rate of units from the resource system to appropriators. Resource systems that have low excludability (and therefore are necessarily shared by multiple appropriators) but produce resource units with high subtractability are defined as CPRs (1990, p. 30).

Together, subtractability and excludability define the relationship between governance and the ecosystem. Institutional actors can choose how to organize the resource system based on subtractability and excludability characteristics inherent to the resource system, making modifications as necessary. Analyzing a resource system's response to use also depends on the relationship between these two characteristics, making it a useful framework for analyzing a CPR's institutional configurations (Oakerson, 1992; E. Ostrom, 1990). While this paper will keep the traditional definition of excludability, it will refine the definition of subtractability by defining the resource unit's relationship both to the appropriators and to the resource system.

Focusing on Subtractability

Subtractability, as mentioned before, has been defined in terms of the resource unit's use being restricted to a single appropriator (E Ostrom, 1990, p. 31). Resource units in this conception tend to resemble parts coming off an assembly line, where the product is a residue of the production process and not integral to the production process itself. However, this paper departs from this assumption in the belief that viewing resource units as entirely separate from the resource system fails to get at the central issue that inspired commons analysis: the appropriation of resource units to the point of resource system failure. To analyze common pool resources, the appropriation of a unit needs to be considered in reference to two different phenomena: one in terms of the resource unit as an appropriable product, the other as part of a resource system's production.

Recognizing the relationship between resource units and resource systems allows us to modify the theory of subtractability to distinguish between the subtraction of a unit among appropriators and that of subtracting a unit from the resource system. The dynamics that define the unit-appropriator relationship, called here instance use, and the unit-resource system relationship, called depletion use, are interconnected to each other but are distinct enough to be considered different concepts.

Instance use refers to the degree to which the resource unit is appropriable at a single point in time by a single appropriator. Subtractability in this sense is observed by looking at the consequences of a unit's subtraction for other appropriators. For some resource system's units, what an appropriator appropriates cannot be appropriated by another. These high instance-use subtractability resource units *have a rate of appropriation dependent on the number of appropriators*. For example, the eating of an apple supplied by an apple tree inherently deprives another from eating the same apple, displaying high subtractability in respect to instance use. In contrast, resources with units that have low instance-use subtractability *have a rate of appropriation independent of the number of consumers*. One person watching television, as an example, does not keep the airwaves from another person watching the same program, demonstrating low subtractability in respect to instance use.

The second component is the relationship of the resource unit's use to the resource system, here called *depletion use*, defined as the marginal quantity of the resource that does and/or can exist after appropriation. Low depletion-use subtractability is characterized *by the rate of depletion being less dependent on appropriation* given the remaining supply and the rate of renewal. Applied to the TV example, the use of airwaves now by the TV watcher will not reduce the station's ability to produce more tomorrow, indicating low depletion-use subtractability. When applied to the apple tree, however, the use of one apple has limited the remaining supply of apples on the tree in the short term but does not limit the tree's ability to produce apples later in time. In other words, the rate of depletion in the remaining supply is balanced by the renewability of the resource. A high depletion-use subtractability would be typified *by a rate of depletion being more dependent on appropriation*. For example, an oil well, as a nonrenewable resource, would have a rate of depletion highly dependent on appropriation. The two elements that create a depletion rate can also be isolated from each other. A resource system that at a point in time displays low depletion-use can become a high depletion-use resource due to natural or anthropocentric processes. An example that will be further elaborated is the isolation of natural inflows into a water basin from urbanization. As water is kept from infiltrating into the groundwater basin, the rate of replenishment declines and results in the depletion rate from appropriation exceeding renewal. In other words, though depletion can be independent from appropriation, it can become dependent after attributes are altered or eliminated. Figure 2 displays the possible combinations of instance and depletion use.

	High Depletion	Low Depletion
High Instance Use	Non-renewable (Oil)	Renewable Resource (Ground Water, Oxygen)
Low Instance Use	Group Resource (Light from a Battery)	Universal Resource (Sunlight)

Fig. (2) Resource Subtractability In Terms of Instance Use and Depletion Use. Source: Author.

Based on the above argument, there are two points worth clarifying. First, it may appear that depletion use is the culmination of instance use. Since depletion use is measured in the aggregate of several actions rather than single actions, it would make sense to think of instance use as subsidiary to depletion. However, this conception of instance and depletion use is mistaken. Instance and depletion-use are referring to two distinct relationships the resource unit has to appropriators and the resource system. As such, both relationships are affected by the characteristics of the resource unit (such as divisibility, quality, conditions for creation, etc.) in their respective aspects of use. Second, based on the two characteristics of a resource unit, traditional subtractability can now be considered a matter of degree (Oakerson, 1992, p. 44). Appropriators and that deplete the resource through instance use are more subtractive than appropriators that do not deplete it. The use of a resource unit is potentially subtractive not only among the current appropriators of the resource but also between present and future appropriators of the resource.

Conceptualizing Resource Subtractability in an Adaptive Cycle

Resilient resource systems, as discussed before, will continue to produce resource units with specific characteristics of quantity and quality despite fluctuations in resource system conditions (C.S. Holling, 1973, p. 14). Instance and depletion use can be applied to the adaptive cycle and the study of resilience by examining how a resource system moves from being renewable to less renewable. Within the new conception of subtractability, shifts in renewability occur in a resource system as the means of resource unit production are destroyed through appropriation. Within this system there are two different manifestations of resource system path dependence. First, the system can be highly resilient but produce sub-optimal resource units. Second, the resource or ecosystems resiliency declines over time as it moves from r to k in the adaptive cycle to the point where the resource system reaches an "collapse" event where the connections between attributes are disrupted and the system ceases to produce units (Gunderson & Holling, 2001, p. 41). In this second case, managers or appropriators may not be aware their resource system is in decline (Scheffer, Carpenter, Foley, Folke, & Walker, 2001, p. 596). In both of these path dependency situations, reforming the resource system is impossible either because it would have to occur over a long time or spatial scale, or because the out-of-pocket or organizational costs would be too high to bring the ecosystem back to its previous state.

Resource System Components

Resource Attributes

Before continuing to discuss adaptive cycles, the proposed relationship between system attributes and a resource system needs to be discussed. Resource system attributes are the elements which interact to form the resource system (Folke, Holling, & Perrings, 1996).[2] Resource system attributes can fall within two different categories. *Endemic attributes* are attributes native to the system that produce the resource units.[3] *Introduced attributes* are foreign to the resource system but interact with other attributes to effect resource unit production. The number of attributes contributes to the wealth of the resource system that can be drawn upon to maintain resource system functions and keep the system resilient (C.S. Holling, 2001, p. 394). What is and is not considered endemic, and therefore introduced, to a resource and ecosystem is a subject of much debate in fields such as ecosystem rehabilitation (Allison, 2017, Chapter 5). For the purpose of this discussion, attributes will be qualified as introduced if they entered a resource system after the exploitation phase and before the collapse phase of the adaptive cycle. Introduced attributes can be physical structures constructed by resource system managers, as well as attributes endemic to other resource systems that have become introduced into the resource system. This type of attribute can affect the resource system adaptive cycle by eroding other or creating new functioning groups (Mäler, 2000). An example of an introduced attribute in this paper will be toxic chemical elements in Southern Californian water tables that subsequently alters groundwater quality (Green, 2007, p. 196).

Related to the discussion of whether an attribute is introduced or endemic is its degree of *durability*, or ability to be passed from adaptive cycle to adaptive cycle. A highly durable attribute does not disintegrate with the conservation or collapse of the adaptive cycle, instead remaining during the reorganization phase of the resource system (Gunderson & Holling, 2001,

p. 8). There can be several reasons for the durability of an attribute, such as the independence of the attribute from other resource system processes, having longer time scales for degradation, or having a massive quantity. A fragile attribute, in contrast, is highly dependent on internal resource system processes to be replenished, a short time scale for degradation, or exists in a relatively small quantity. A highly durable attribute can be passed through an adaptive cycle, while a fragile attribute is more likely to be lost as a result of the collapse. Depending on how durable attributes relationship to other attributes in structuring the resource, the collapse of a single attribute may lead to the collapse of the entire system.

Functional Groups

Resource attributes form functional groups that perform similar functions within the resource system (Cleland, 2011). Diverse sets of attributes performing a similar function ensures that the resource system can respond to changes and provide units despite fluctuations in ecosystem or resource system conditions (Elmqvist et al., 2003, p. 490). Even as these destructive events may reduce or eliminate certain attributes, the system can compensate by drawing on rich sets of redundant attribute configurations. In short, diversity begets redundancy so that as attributes degrade or reconfigure, resource system output remains consistent (Peterson et al., 1998, p. 14).

Attributes can be shared among several resource systems within an ecosystem since it can be a part of different functioning groups that produce a resource unit. The shared attributes in turn are configured to produce different processes in respect to their involvement in different functioning groups that compose resource systems. The overlap in key structuring attributes and mutual reinforcement are what give a resource system resilience (Peterson et al., 1998, p. 13). In ecology, these structuring attributes are referred to as ecosystem drivers (B. H. Walker, 1992, p. 20). Ecosystem drivers physical structure to their resource system, or have strong interactions with other attributes that allow the ecosystem to function (1992, p. 20). In turn, these attributes promote key resource system processes that provide ecosystem services across time and spatial scales (C. S. Holling, 1992). A diverse number of driver attributes provide greater stability to their resource system and create a mutually reinforcing mechanism to keep the system in its current state (Elmqvist et al., 2003, p. 488). Based on the number of driver attributes in the same functional group, resource systems can flip into alternative stable states as resource attributes are lost and resilience decreases (Folke et al., 2012, p. 573). Alternatively, since the processes that provide resource system structure are based on specific attributes, variations in those attributes can decide later outputs or the trajectory of the cycle.

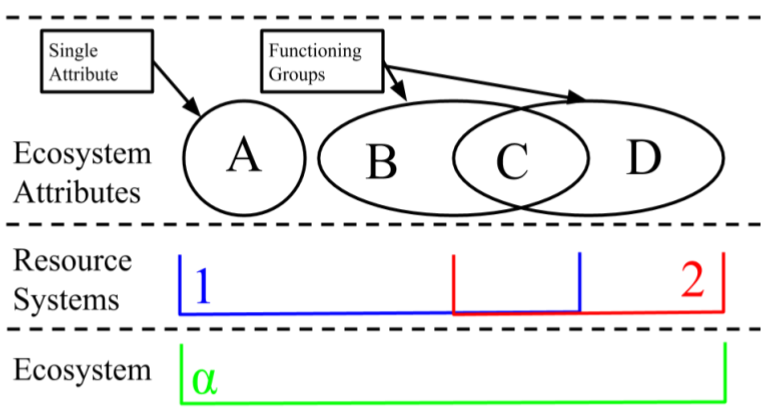

Fig. 3: Example of the Relationship Between Attributes, Functional Groups, Resource Systems and the Ecosystem. Source: Author.

Resource Systems

Resource attributes, as stated before, interact to create resource units through resource system processes. The processes between the attributes maintain balance between them and allow for the resource system to self-regulate the arrangements between attributes (Peterson et al., 1998, p. 14). Resource system processes occur as attributes' relationships are adjusted in quantity, spatially, and temporarily, thereby adjusting their relationship to each other. Resource system governance in this framework facilitates two operations on the resource system; the collective actions of appropriators, and the maintenance of structuring attributes of the resource system, such as engineered attributes, by managers. Management and appropriation activities then maintain the resource system as appropriators and managers adapt to modify system conditions (V. Ostrom & E. Ostrom, 1977).

Renewable and non-renewable resource systems are distinct from universal and group resources in that one or more of their attributes form the resource unit being appropriated from the resource system. The degradation of a resource system therefore occurs as the resource system attribute degrades over time, which does not allow for its recovery through supporting attributes. The loss of the resource attribute hampers future production of resource units as a result.

Applying the Adaptive Cycle Model

Decline through Attribute Loss

An adaptive cycle provides a model for representing the history of a resource system-unit relationship in two distinct ways. First, an adaptive cycle can represent resource system decline from resource unit loss. As the number of attributes in the system decreases, the system's stability declines as well (Folke et al., 1996, p. 1019). Applied to the adaptive cycle, systems in the r phase of development have built in redundancy due to a proliferation of diverse functional groupings of attributes that produce similar self-maintaining processes within the resource system. Redundancy is lost over time as the system moves from the r to k phase as shorter timescale attributes are pushed out by attributes with greater longevity as well as through over-appropriation (C.S. Holling, 1986, p. 96). As the system becomes more reliant on attributes that have longer lifespans and are slow to replenish, the system gradually loses the attribute diversity that supports resource system processes. The resource system is subsequently susceptible to disturbances, increasing the likelihood of resource system degradation or collapse (C.S. Holling, 1986, p. 96). Therefore, resource managers need to maintain significant redundancy in a functioning group to sustain the production of resource units (Folke, Holling, & Perrings, 1996).

Attribute Loss from External System Collapse

Attribute loss to the point of collapse is associated with two different situations. The first is the disruption to large-scale adaptive cycles that support smaller cycles (C. S. Holling, 2001, p. 398). Since large time and spatial scale processes create a foundation for the faster and smaller systems, disruptions in the slower cycle are likely to modify resource system attributes at lower levels (2001, p. 398). Attribute loss at lower levels reduces resilience within the system. In terms of resource unit production, such changes can destroy connections between a resource system's attributes that produce resource units. Smaller cycles can, as a result, become completely reorganized due to the destruction of a slower adaptive cycle (Scheffer et al., 2001).[4] The loss of attributes in these cases is considered external to the resource system and possibly ecosystem.[5]

Gradual Attribute Loss

The second way system change can occur is through a gradual loss of attributes that leads to decreasing diversity in functioning groups (Folke et al., 2012, p. 570). In these cases, systems are allowed to become stuck in a fixed pattern of use that allow them to become increasingly vulnerable to changes in the higher cycles in the panarchy, and, in other words, lose resilience (C. S. Holling, 2001, p. 399). Unlike the stochastic change in a higher panarchic level leading to a loss in attribute diversity, the loss of resilience in a system is due to the collapse of a single cycle. In these cases, it can be possible that the large scale cycle will remain unaffected until a number of lower cycles fail and begin a shift in the larger spatial scale (C.S. Holling, 2001, p. 398; Rietkerk, Dekker, Ruiter, & Koppel, 2004, p. 1928).

Both attribute loss scenarios have common characteristics, the first being that system processes are developed out of hysteresis. In processes characterized by hysteresis, it is not possible to go back to the ecosystem's initial state by simply reversing the actions taken by actors to get to achieve the current state (Mäler, 2000). Hysteresis accounts for the effect of human activities on transforming the relationship between resource units and the resource system. In the case of externally-based system collapse, human management activity collapses the underlying adaptive cycle so that the system undergoes a rapid and catastrophic change that cannot be reversed (Scheffer et al., 2001). Similarly, in the internal collapse model a system change can occur as an effect of over-appropriating a resource unit to the point where there it can no longer recover (Folke et al., 2012, p. 568).

Role of Governance in Resource Unit Production

An adaptive cycle can also represent the effects of appropriator and manager governance on the relationship between resource system output. Resource system attributes in an adaptive cycle can be relatively flexible in their relationship to each other, given their redundancy. As renewable resource systems can have multiple different attributes in the same functional group, they can have similar appropriative properties as well and can be appropriated interchangeably (C.S. Holling et al., 2009, p. 57). The redundancy in a resource system allows it to function even as a single resource attribute is diminished (B. H. Walker, 1992, p. 20). Dynamics in the ecosystem or external system can allow for resource attributes to be replenished based on the attribute's requirements for existence within the resource system.[6] By examining what attributes are present in the resource system after appropriation and management activity, the system's progress toward collapse can be assessed to see if it has already crossed a threshold(Folke et al., 2002, p. 440).

Resource System Path Dependence

Having established how a resource system's adaptive cycle can be used to examine internal resource system dynamics that lead to collapse, we can move on to examine how resource system path dependence can emerge out of processes related to attributes. Path dependence is well-suited to the study of natural resource systems, and by extension SES's, since it operates on the assumption of multiple equilibria based on appropriators adopting a strategy that suits their needs (Pierson, 2000, p. 263). Markets for products are conceived in a similar way in economics, and was the first focus for research on path dependence. Since these products are subject to *increasing returns*, or that the product gets easier to use and cheaper to access as it is proliferated, other possibly superior options on the market become excluded and can no longer be pursued (Arthur, 1989, p. 116; David, 2007, p. 10). The most common subject for path dependence analysis is technology adoption, such as in the now-famous studies on QWERTY keyboards (See David, 1985). In political science, increasing returns for a strategy or institution are assumed to occur as they ease decision-making process and become increasingly efficient the more they are adopted (Hathaway, 2003) or as political bodies are coordinated (Pierson, 2000).

Unlike economic path dependence analysis, resource path dependence does not focus on the adoption of a product, as there is no choice between pursuing one resource system unit over another resource unit.[7] While path dependence here then follows political science's focus on strategy and institutional adoption, it is distinct in that the path dependence is based on the physical constraints of what is being governed rather than strictly organizational costs. In resource system path dependence, management and appropriation decisions create path dependent behavior by selectively modifying certain resource system attributes through appropriation and management operations. Choices in the strategy supported by institutions regulating management and appropriation activities are assumed to be random, since several different options are open to resource system beneficiaries in how they organize their resource systems (B. Walker, Holling, Carpenter, & Kinzig, 2004, p. 3). Choices are subject to lock-in as adoption continues, resulting in a poorly configured resource system (Pierson, 2000, p. 258). In other words, resource units have either become absent from the system entirely or exist in a form that cannot be used by appropriators. Modifying the resource unit or the resource system would have prohibitively high costs, preventing necessary changes (See Green, 2007).

Manager and appropriator operations result in resource system path dependence by modifying system attributes. This can happen in four different ways: attribute subtraction, dysfunctional endemic engineered attributes, self-proliferating introduced attributes, and negative effects on cross-system attributes. The first type of management operation that can cause resource system path dependence is subtractive activities that result in resource system collapse. Classic examples of this can be found in overgrazing a grassland (See Ludwig, Walker, & Holling, 1997) overfishing a fishery, (See Berkes, 1992), or logging (See Hart, 1998, p. 67). In these cases, the resource system either collapsed and stopped producing resource units (as in the case of the grasslands that converted into shrub bush land (Ludwig et al., 1997) and fisheries that could no longer produce fish (See Berkes, 1992)) or began to produce resource units that were unusable by beneficiaries (such as hardwood succession of pine forest (See Hart, 1998, p. 67)). In these cases, managers allowed for appropriation activity that reduced the diversity of system attributes. The appropriating activities also did not allow the resource attribute to recover with the support resource system or did not provide an artificial counteractive activity to replenish the system attributes.

Resource system path dependence by attribute subtraction occurs through a reduction of the number of attributes in the same functioning group. The loss of a single attribute, while compromising the redundancy of the resource system to maintain function after a stochastic event, is unlikely to move the resource system into a collapse phase. Comparable resource units can be found as an alternative for the lost attribute, such as in the case of fisheries which move from focusing on one type of fish to another (E. Ostrom, 1990, p. 173). In these cases, the behavior is not yet considered to be path dependent. The management method, while being destructive to future management strategies, has not limited the scope of options to a degree that they cannot create solutions. However, a threshold for overall system stability has been crossed with the loss of an attribute, and if institutional actors are not responsive, it could result in the collapse of the resource system. (Folke et al., 1996, p. 1022). As the management method becomes widely adopted it experiences increasing returns, and as more thresholds are crossed, the range of future management strategies become increasingly limited (C. S. Holling, 2001, p. 322). In the adaptive cycle model, this would be represented by a gradual move from r to k as the system losses attribute diversity and begins to fail.

The second source of resource path dependent behavior is through engineered endemic attributes. This type of resource system path dependence arguably bears the most resemblance to traditionally recognized path dependence, since it examines the historical effect of choosing a product on subsequent iterations of management strategy. Engineered endemic attributes play a structuring role in resource system patterns of interaction and create path dependent behavior in that, once they are integrated, they cannot be easily eliminated. The integration of an engineered attribute into a resource system implies that an engineered attribute must be durable to be able to create path dependent behavior. For example, the Zanjera system of irrigation in the Philippines (E Ostrom, 1990, p. 82) cannot be described as displaying path dependence inherent to engineered systems since the infrastructure breaks down so quickly. However, structures like dams can be considered path dependent given the large amount of investment that is required to build and their difficulty to destroy. They may also be subject to increasing returns in that they need to be integrated at a large spatial and temporal scale to be effective. Smaller engineered attributes may be easier to remove or modify when management strategies need to shift, but at a certain size the consequence of eliminating them may come at the expense of other systems or may simply be impractical. The problems associated with dam removal to give salmon greater access to breeding grounds in the northwest may be an example of resource system path dependence with such endemic attributes (Protection Committee on Salmonids Management of Pacific Northwest Anadromous, 1996). Thus, management strategies after the dam is built become relatively inflexible in some areas, leading to sub-optimal output.

The third type of resource system path dependence comes from introduced attributes. Attributes are sometimes introduced by managers or beneficiaries to modify the resource system in some way. Ecology provides several different examples of introduced attributes having severe effects on endemic attribute processes, such as the zebra mussel's effect on Great Lakes infrastructure (O'Neill, 1997) and runoff from nitrated fields into a lake (Mäler, 2000, p. 651). In these cases, managers and appropriators created sub-optimal outcomes for their resource system. As in the case of endemic attributes, introduced attributes are assumed to be relatively durable and have persistent effects on the resource system processes. However, while introduced attributes do not play a key role in resource system structure since they were not present at system formation, they can affect key system attributes by reducing their quantity or what effect they have on the system. Appropriators and managers in these cases are not the ones propagating the attribute; the resource system's internal processes scale up the effect of the attribute on resource system functions. Introduced attributes can then begin to degrade the current resource system, and in the event of resource system failure become integrated into a new resource system that may not produce the desired resource units for appropriators. The costs to institutional actors are from efforts to reduce the introduced attribute's effects, since elimination is rarely if ever feasible. Governance is then challenged to create manager and appropriator operations that have efficient returns to scale or introducing a crutch for the resource system. Ecological examples of attribute control include sea lampreys in the Great Lakes ("Lampricides and Sea Lamprey Control," n.d.), purple loostrife in Ontario (Warne, 2016), and the brown-headed cowbird in Texas (Siegle & Ahlers, 2004).[8] In these cases, the cost of eliminating the new introduced attribute may be prohibitively expensive for managers and appropriators.

The fourth source of resource system path dependence is cross-system attribute modification. In these cases, the shift, introduction or elimination of an ecosystem attribute that is innocuous or beneficial to one resource system effects the governance of another to create an irreversible resource system decision. Oftentimes this is a key structuring element for resource system functions (B. H. Walker, 1992, p. 20). Cross-system effects may arise out of governing appropriators and managers failing to coordinate an ecosystem management strategy, or policy decisions prioritizing the wellbeing of one system over another. An example of a single attribute having effects across multiple resource systems would be a 'keystone species', or a single species that is essential to normal ecosystem functioning (Mills, Soulé, & Doak, 1993). As appropriators and managers can reduce the keystone species, related resource systems would begin to fail or produce sub-optimal results due to interference in system processes.

Oftentimes the pursuit of one resource system over another is a result of increasing returns, since as appropriators and managers increase or decrease a certain attribute, the greater the benefit for the priority system. As other surrounding resource systems become degraded, managers are forced to keep focusing on the priority resource system, reducing their ability to pursue other ecosystem management strategies. Such ranking of resource systems by priority can emerge out of chance occurrences in governance arrangements. For example, the water quality and recreational opportunities in Hamilton Harbor in Ontario, Canada, has been limited by a constitutional level rule in the harbor's charter in the account by Sproule-Jones (1993). The provision made the harbor independent from national regulation and subsequently gave full priority to shipping interests. As a result, there are few ways to regulate water pollution from ships since water quality does not naturally or institutionally impede shipping operations. The subsequently poor water quality reduces recreational management options in the harbor, as well as the other resource systems that provide services to public health. The range of choices for those resource systems is therefore reduced and can become unalterable.

Resource system path dependence can be seen to encompass several different phenomena where resource systems become degraded as a result of resource attribute reconfiguration. Multiple sources of resource path dependence can exist in a single resource system, and the ability to diagnose those issues may be a key strength to this type of analysis when looking at SESs.

Resource Path Dependence Case Study: Groundwater Management in Southern California

Southern Californian groundwater management has become a classic example of public entrepreneurship, polycentricity, and institutional robustness (Blomquist, 1992; E Ostrom, 1990, Chapter 4). One of the reasons for the region's success has been preventing two of the path dependence phenomenon discussed above; subtractive path dependence from water withdrawal, and cross-system path dependence from other subterranean systems. Managers and appropriators have developed strategies and collaborations to prevent themselves from creating path dependent situations as well as flexible to protect its attributes (See Antos, 2016). Resource system managers are also able to combat sources of path dependence by virtue of the area's wealth. As a result, they have been able to undo what in many areas would be considered permanent damage to the ground water system (Green, 2007). However, given the large amount of time it takes managers to finish the cleanup process of a basin, managers have consistently sought to avoid strategies that could limit the use of groundwater in the future.

Southern California's Subsurface Ecosystem

Attributes and Functioning Groups

Groundwater is fed by rain, overlying rivers, snowmelt and water spreading as it percolates through the soil and into the aquifer (Quevauviller, 2008, p. 4). Water accumulates in the basin over time and can create underground flows that act like rivers as they make their way to the sea or support riparian flows above them (2008, p. 6). Water is accessed through well pumping, where water is drawn out of the ground based on well depth and groundwater level (2008, p. 6).

Groundwater in Southern California, as in most places, is considered a common pool resource, given its low natural excludability and the high subtractability. There are no natural barriers that limit pumpers on overlying land from drilling into the earth to create the shafts needed to draw water. Groundwater is also highly subtractive for two reasons. First, water appropriated by one appropriator cannot be used by others. Second, water appropriation can cause the water table to fall if there are insufficient inflows into the basin. Using the subtractability language described above, the resource can be described as having high instance use and, depending on the condition of resource attributes, high depletion use. The groundwater basin can therefore be described as a common pool resource that, depending on use, can shift from a renewable to non-renewable or less-renewable resource system.

Groundwater basins have several different attributes that provide stability for the system and give it the characteristics of a renewable resource. Water inflows form the first functional group of attributes and can be appropriated by resource system appropriators through pumping.

Inflows have specific qualities based on their source, such as high-quality recycled water and impure runoff from streets and roofs (Green, 2007). The water also gives the basin certain chemical characteristics, such as salinity, depending on how much water is in the basin (Vengosh, 2003).

The second major functioning group is soils, ranging in characteristics in terms of chemical composition, space between particles, and spatial position within the basin (DWR, 2003, p. 83). Basin soils are difficult to decontaminate, existing within the basin for centuries without certainty of success in any remediation efforts (Scholz & Schnabel, 2006).

The third group of attributes are geological formations. The geological attributes, such as basin size, fault lines, and undulations, create the structure of the basin, and affect how water flows through it (Winter, 1999). Geological attributes, like soil composition, are highly durable, since they cannot be modified at all by managers. Water attributes are configured based on these geological and soil attributes, and their subsequent effects on water flow and quality.

Sources of Path Dependence

Groundwater systems can display path dependence based on the durability of their attributes and system dynamics. Alterations to durable attributes, as will be recalled, are difficult to alter by resource system managers, and can have permanent effects on resource system processes. Over-pumping can have such effects on durable attributes, changing a basin forever through compaction and salinization (Galloway, Jones, & Ingebritsen, 1999; Vengosh, 2003). While it will not immediately cause these effects, it will only do so over time as more water is removed from the basin. By the time the effects are noticed by managers, however, irreversible damage to storage capacity and basin functioning may have occurred (Langridge, Brown, & Rudestam, 2016, p. 163). Over-pumping therefore lowers the resilience of the basin, creating a shift that may progress as the practice continues. In the language of path dependence, this is a "lock-in" effect, where future use options or management strategies are foreclosed due to initial practices.

Polluting a basin through non-extractive activities can also have unalterable effects on groundwater systems by altering water quality, such as chemical contamination through improper waste storage (Langridge et al., 2016, p. 151). Oftentimes these issues emerge as attributes in one of the groundwater resource system's functioning groups are incorporated into another resource systems set of attributes. In the case of chemical contamination, soil attributes that contain the waste are the same attributes that give water certain chemical properties. The overlaps in functioning groups meet the criteria for a cross-system governance effect. These attribute effects can be dramatically increased by appropriator and manager actions. For example, the continued pumping of water by appropriators close to a chemical contamination site often spreads the pollutant, affecting more appropriators and making chemical issues widespread (Ali, 2016, p. 150; Green, 2007). While basins can be cleaned, it comes at an extremely high out-of-pocket and decision-making costs, along with lower resource system productivity. Chemical characteristics can be highly durable and have a large effect on future groundwater appropriator activity.

Another cross-system management issue can occur through the elimination of an attribute from the groundwater resource system, such as precipitation and riparian inflows as a result of paving. In this case, the groundwater system shares a portion of its functional groups for soils and water inflows with riparian resource systems. Porous top soils facilitate riparian inflows of water into the groundwater basin and are a part of that attribute's characteristics. In Southern California the riparian resource system has been heavily modified by resource system managers for the purposes of flood control. A part of the riparian manager's operations has been to pave streams and drainage areas, in effect solidifying the topsoil to create an engineered attribute that prevents water infiltration. Since pavement and chemicals are durable and cannot be easily changed, they affect the functioning of groundwater resource systems.

These management strategies can become locked-in as resource attributes are altered and the system crosses thresholds nearing the collapse phase. Such effects pose threats to groundwater basin management in Southern California. General strategies for resource use have shifted away from purely extractive to storage (Green, 2007, p. 22). Managers and appropriators then need to develop manager and appropriator operations through governance practices that can prevent resource attribute loss.

Water Rights and Original Management

California has two different legal categories that are used to classify a water right. The first category is based on land ownership. A right holder that owns land above or beside the water source has an overlying right, while a non-overlying right is classified as appropriative (Green, 2007; Blomquist, 1992, Wendell, 2015). Appropriative rights are inferior to overlying or riparian rights and can only be created if the producers have excess water (Blomquist, 1992; Hanemann, Dyckman & Park, 2015; Wendell, 2015).[9] For all types of rights, there exists the principle of 'first in time, first in right' . Senior water producers have a superior right to junior producers and therefore can receive water before them if the flow begins to dissipate (Blomquist, 1992; Hanemann, Dyckman & Park, 2015; Wendell, 2015). Inferior rights holders can come to possess a superior right if they take more than their allocation to water over a 5-year period without the superior holder taking them to court. After 5 years, the right solidifies into a legitimate right to the increased water allocation.

Over time, the differences between the types of rights create distinct path dependence issues for groundwater appropriators, the largest being through so-called "pumping races" as they pump independently. These races occur as junior appropriative rights holders seek to solidify their right to water over senior overlying holders by taking excessive amounts of water. Overlying owners seek to solidify their rights in response, fearing to take appropriative right holders to court for fear that the appropriator will be within their rights to water or that appropriators right would have solidified into a permeant right (Blomquist, 1992, p. 68). In these cases, there would be increasing institutional returns as the right to water solidified over other appropriators. Such strategies would reduce future resource unit production as well as future management strategies, such as water capture and storage, through eliminating vital resource attributes. The system would then be depleted, and the renewability of the resource diminished. Future opportunities to operate the resource as renewable would be foreclosed, locking in the appropriators to a suboptimal strategy until the water ran out.

Groundwater Agencies

Water appropriators in Southern California have been given significant power by court arbitrations to create institutions and governance structures that suit their own needs. Examples of this power was seen in the several groundwater adjudications that took place from the 1940's to the 1960's, where adjudication created new appropriator-developed organizations with defined parameters, and held them accountable to the court (Green, 2007; Blomquist, 1992). Since appropriator organizations were legitimated by the state through judicial oversight, they could operate and redefine themselves over time as the resources they depended on fluctuated (Blomquist). These cases reveal the role of the court as a higher-level collective choice arena that can supersede established appropriator operations. The courts can also create governance opportunities that encourage sustainable resource use by allowing appropriators and managers to create new resource governance structures. The principles of water property rights outlined above are considered as the basis of water allocations, but the original terms of the right do not apply to the allocations themselves. Altering collective choice rule configurations preserves resource system attributes and therefore allows for greater flexibility for future resource management objectives.

To protect against over-extraction, producers have had their rates mutually adjusted to be within the basin's safe limit (Blomquist, 1992; Hanemann, Dyckman & Park, 2015). These rights are unique to each resource system, and act as membership into the groundwater organization created by the adjudication (Blomquist, 1992). These organizations monitor pumping and enforce regulations through collective litigation based on the terms of the adjudication (Blomquist, 1992, p. 10). Groundwater organizations operate in the geographic area of the basin, using its boundaries as the limits of its jurisdiction (Blomquist, 1992). Water-masters are at the head of the organizations, and act as an unbiased party in administering pumping rights and regulations on water quality (Green, 2007). For example, water-masters have the authority to limit the extraction of water when basin contamination is severe in order to prevent its spread. In most cases, the Department of Water Resources (DWR) acts as the water-master, but other times the role has been assigned to a more local entity, such as in the case of the Main San Gabriel Water-Master (Blomquist, 1992, p. 174). The opportunities available for appropriators to form stakeholder-driven groundwater governance has led to the creation of a diverse set of institutions that vary in scope, rules and regulations (Blomquist, 1992). These agencies are often used to coordinate water allocation trades, water spreading, saltwater intrusion barriers, basin decontamination, and other services that could not be handled by individual appropriators or smaller groups (Blomquist, 1992, p. 151; Green, 2007, p. 65).

Despite the development of agencies and new approaches to management, groundwater systems do not function well in some areas. Before the effects of waste dumping on groundwater quality were well known, a significant quantity of toxic substances was unsafely deposited in many basins around Southern California (Blomquist, 1995; Atwater, 2002; Green, 2007). The effects of basin pollution on groundwater production vary, but with current technology, certain basins will take a long time to clean up (Green). While appropriators have been good at coordinating the prevention of pollution spreading by collective action, the loss of storage will continue to impact future water use due to path dependence (Green 2005, Pinectl 2016, Porse 2016).

Conclusion

Resource system path dependence is a tool that can be used to track management strategies that degrade resource systems, resulting in a diminishment or complete elimination of resource units. The concept can be best outlined by analyzing a resource system in terms of its component parts, i.e., its resource system attributes, and determining the characteristics and function of the attributes within the resource system, as well as groups of attributes that create redundancy within the resource system. By finding the relation between resource attributes, the approximate effects of management can be determined for each set of operations available to appropriators and managers. In renewable resource systems, system attributes form resource units that are withdrawn by appropriators. Over-appropriation can result in resource system degradation, shifting a resource system from renewable to non-renewable. Resource systems are found to be highly interconnected within the same ecosystem, and while providing several different services, renewable systems can become subject to degradation as resource attributes are lost. Adaptive cycles and the concept of resilience are important to understanding the degradation process and the point where resource systems fail to produce desired resource units as redundancy is lost and the system becomes fragile. Path dependence can occur when options for management and use are reduced as attributes are altered. An example of this phenomenon and its prevention can be seen in the case of Southern California groundwater management, as managers seek to prevent attribute loss and keep management strategies flexible. By recognizing resource system path dependence, managers and appropriators can avoid sub-optimal resource unit production and resource system destruction.

Bibliography

Ali, M. H. (2016). *Principles and Practices of Water Resources Development and Management*. Hauppauge, New York: Nova Science Publishers, Inc. Retrieved from http://proxy.houghton.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=e000xna&AN=1350573&site=ehost-live&scope=site

Allison, S. K. (2017). Ecological restoration and environmental change. In *Routledge Handbook of Ecological and Environmental Restoration*. London, UK: Routledge. https://doi.org/10.4324/9781315685977

Anderies, J. M., Janssen, M. A., & Ostrom, E. (2004). A Framework to Analyze the Robustness of Social-ecological Systems from an Institutional Perspective. *Ecology and Society*, *9*(1), art18. https://doi.org/10.5751/ES-00610-090118

Antos, M. (2016). *Social-Ecological and Institutional Barriers to Adaptive Water Management*. University of California Los Angeles. Retrieved from https://escholarship.org/uc/item/0gt1n048

Armitage, D. (2008). Governance and the commons in a multi-level world Derek. *International Journal of the Commons*, *2*(1), 7–32. https://doi.org/10.1080/10826079308019552

Arthur, W. B. (1989). Competing technologies, Increasing Returns, and Lock-in. *The Economic Journal*, *99*(394), 116–131. https://doi.org/10.2307/2234208

Barrett, K. R. (1999). Ecological engineering in water resources: The benefits of collaborating with nature. *Water International*, *24*(3), 182–188.

Berkes, F, Folke, C., & Colding, J. (1998). *Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience*. (Fikret Berkes & C. Folke, Eds.) (1st ed.). Cambridge, UK: Cambridge University Press. Retrieved from https://books.google.com/books?id=Q9E_ngEACAAJ

Berkes, Fikret. (2009). Evolution of co-management : Role of knowledge generation , bridging organizations and social learning. *Journal of Environmental Management*, *90*(5), 1692–1702. https://doi.org/10.1016/j.jenvman.2008.12.001

Blomquist, W. (1992). *Dividing the Waters: Governing Groundwater i Southern California*. San Francisco: ICS Press. https://doi.org/10.1080/00358535508451943

Bromley, D. W., & Feeny, D. (1992). *Making the Commons Work: Theory, Practice, and Policy*. ICS Press. Retrieved from https://books.google.com/books?id=OTmFAAAAIAAJ

Cleland, E. E. (2011). Biodiversity and ecosystem stability. *Nature Education Knowledge*, *3*(10), 14.

David, P. A. (1985). Clio and the Economics of QWERTY. *The American Economic Review*, *75*(2), 332–337. Retrieved from https://www.jstor.org/stable/1805621

David, P. A. (2007). Path Dependence: A Foundational Concept for Historical Social Science. *Cliometrica*, *1*(2), 1–26. https://doi.org/10.1007/s11698-006-0005-x

Decaro, D., Chaffin, B. C., Schlager, E., Garmestani, A. S., & Ruhl, J. B. (2017). Legal and Institutional Foundations of Adaptive Environmental Governance. *Ecology and Society*, *22*(1). https://doi.org/10.1017/CBO9781107415324.004

DWR. (2003). Basic Groundwater Concepts. In *CALIFORNIA'S GROUNDWATER UPDATE 2003 (DWR Bulletin 118)* (pp. 79–104). Sacramento: DWR. Retrieved from https://water.ca.gov/LegacyFiles/pubs/groundwater/bulletin_118/california's_groundwater__bulletin_118_-_update_2003_/bulletin118-chapter6.pdf

Elmqvist, T., Folke, C., Nyström, M., Peterson, G., Bengtsson, J., Walker, B., & Norberg, J. (2003). Response diversity, ecosystem change, and resilience. *Frontiers in Ecology and the*

Environment, *1*(9), 488–492. https://doi.org/10.1890/1540-9295(2003)001[0488:RDECAR]2.0.CO;2
Folke, C., Carpenter, S., Elmqvist, T., Gunderson, L., Holling, C., & Walker, B. (2002). Resilience and Sustainable Development: Building Adaptive Capacity in a World of Transformations. *Ambio*, *31*(5), 736. https://doi.org/10.1579/0044-7447-31.5.437
Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., & Holling, C. S. (2012). Regime Shifts, Resilience, and Biodiversity in Ecosystem Management. *Annual Review of Ecology, Evolution, and Systematics*, *35*(2004), 557–581. https://doi.org/10.2307/annurev.ecolsys.35.021103.30000021
Folke, C., Holling, C. S., & Perrings, C. (1996). Biological Diversity, Ecosystems, and the Human Scale. *Ecological Applications*, *6*(4), 1018–1024.
Gallopín, G. (2007). LINKAGES BETWEEN VULNERABILITY, RESILIENCE, AND ADAPTIVE CAPACITY. In *Workshop "Formal Approache to Vulnerability."* Potsdam, DE: Potsdam Institute for Climate Impact Research September. https://doi.org/10.1016/j.gloenvcha.2006.02.004
Galloway, D., Jones, D. R., & Ingebritsen, S. E. (1999). *Land Subsidence in the United States*. Reston, VA. Retrieved from https://pubs.usgs.gov/circ/1999/1182/report.pdf
Green, D. (2007). *Managing Water: Avoiding Crisis in California*. University of California Press. Retrieved from https://books.google.com/books?id=6QmFF0e52TkC
Gunderson, L. H., & Holling, C. S. (2001). *Panarchy: Understanding Transformations in Human and Natural Systems*. Island Press. Retrieved from https://books.google.com/books?id=o4u89akUhJMC
Hart, J. F. (1998). *The Rural Landscape*. Baltimore, MD: Johns Hopkins University Press. Retrieved from https://books.google.com/books?id=OqQ6K3lGGooC
Hathaway, O. A. (2003). Path Dependence in the Law- The Course and Pattern of Legal Change in a Common Law System, 101–165.
Holling, C. (1996). Engineering Resilience versus Ecological Resilience. In *Engineering Within Ecological Constraints*. https://doi.org/10.17226/4919
Holling, C. S. (1992). Cross-scale morphology, geometry, and dynamics of ecosystems. *Ecological Monographs*, *62*, 447–502.
Holling, C. S. (2001). Understanding the Complexity of Economic, Ecological, and Social Systems. *Ecosystems*, *4*(5), 390–405. https://doi.org/10.1007/s10021-00
Holling, C.S. (1973). Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics*, *4*, 1–23. Retrieved from https://www.jstor.org/stable/2096802
Holling, C.S. (2001). Understanding the Complexity of Economic, Ecological, and Social Systems. *Ecosystems*, *4*(5), 390–405. https://doi.org/10.1007/s10021-00
Holling, C S, Allen, C. R., & Gunderson, L. H. (2009). *Foundations of Ecological Resilience*. Washington, DC: Island Press. Retrieved from http://proxy.houghton.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=e000xna&AN=382538&site=ehost-live&scope=site
Holling, Crawford S. (1986). The resilience of terrestrial ecosystems: local surprise and global change. *Sustainable Development of the Biosphere*, *14*, 292–317.
Lampricides and Sea Lamprey Control. (n.d.). Retrieved from http://www.glfc.org/lampricide.php
Langridge, R., Brown, A., & Rudestam, K. (2016). *An Evaluation of California's Adjudicated Groundwater Basins*. Santa Cruz, CA. Retrieved from

https://escholarship.org/uc/item/71n7v525
Ludwig, D., Walker, B., & Holling, C. S. (1997). Sustainability, stability, and resilience. *Conservation Ecology*, *1*(1).
Mäler, K.-G. (2000). Joseph Schumpeter Lecture | Development, ecological resources and their management: A study of complex dynamic systems. *European Economic Review*, (44), 645–665. Retrieved from https://esanalysis.colmex.mx/Sorted Papers/2000/2000 SWE -Hyd Econ.pdf
Mills, S. L., Soulé, M. E., & Doak, D. F. (1993). The Keystone-Species Concept in Ecology and Conservation. *BioScience*, *43*(4), 219–224. Retrieved from https://www.jstor.org/stable/pdf/1312122.pdf
O'Neill, C. R. (1997). *Economic Impact of Zebra Mussels-Results of the 1995 National Zebra Mussel Information Clearinghouse Study*. *Great Lakes Research Review* (Vol. 3). Retrieved from https://cybercemetery.unt.edu/archive/nisic/20110630015418/http://www.aguadelastrobrasil.org.br/arquivos/31.pdf
Oakerson in Bromley, D. W., & Feeny, D. (1992). *Making the Commons Work: Theory, Practice, and Policy*. ICS Press. Retrieved from https://books.google.com/books?id=OTmFAAAAIAAJ
Oakerson, R. J., & Walker, S. T. (1997). Analyzing policy reform and reforming policy analysis: an institutionalist approach. *Policy Analysis Concepts and Methods: An Institutional and Implementation Focus*, *5*, 21–53.
Ostrom, E. (1990). *Governing the Commons: The Evolution of Institutions for Collective Action* (1st ed.). Cambridge, UK: Cambridge University Press. Retrieved from https://books.google.com/books?id=4xg6oUobMz4C
Ostrom, E. (2005). *Understanding Institutional Diversity*. Princeton NJ: Princeton University Press. Retrieved from https://books.google.com/books?id=-s5tQgAACAAJ
Ostrom, Elinor, & Cox, M. (2010). Moving beyond panaceas: A multi-tiered diagnostic approach for social-ecological analysis. *Environmental Conservation*, *37*(4), 451–463. https://doi.org/10.1017/S0376892910000834
Ostrom, V., & Ostrom, E. (1977). Public Goods and Public Choices. *Alternatives for Delivering Public Services: Toward Improved Performance*, 7–49. https://doi.org/10.1007/978-3-662-44143-5_5
Peterson, G., Allen, C. R., Peterson, G., Allen, C. R., & Holling, C. S. (1998). Ecological Resilience, Biodiversity, and Scale. *Ecosystems*, *1*, 6–18.
Pierson, P. (2000). *Increasing Returns, Path Dependence, and the Study of Politics*. *Source: The American Political Science Review* (Vol. 94). Retrieved from https://www.jstor.org/stable/pdf/2586011.pdf
Protection Committee on Salmonids Management of Pacific Northwest Anadromous. (1996). *Upstream: salmon and society in the Pacific Northwest*. Washington, DC: National Academy Press.
Quevauviller, P. (2008). *Groundwater Science and Policy : An International Overview*. Cambridge: Royal Society of Chemistry. Retrieved from http://proxy.houghton.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=e000xna&AN=496355&site=ehost-live&scope=site
Rietkerk, M., Dekker, S. C., Ruiter, P. C. De, & Koppel, J. Van De. (2004). Self-Organized Patchiness and Catastrophic Shifts in Ecosystems, *305*(September), 1926–1929.

Scheffer, M., Carpenter, S., Foley, J. A., Folke, C., & Walker, B. (2001). Catastrophic shifts in ecosystems. *Nature*, *413*(October), 591–596.

Scholz, R. W., & Schnabel, U. (2006). Decision making under uncertainty in case of soil remediation. *Journal of Environmental Management*, *80*(2), 132–147.

Schreyögg, G., & Sydow, J. (2011). Organizational Path Dependence: A Process View. *Organization Studies*, *32*(3), 321–335. https://doi.org/10.1177/0170840610397481

Siegle, R., & Ahlers, D. (2004). *Brown-Headed Cowbird Management Techniques*. *US Department of the Interior, Bureau of Reclamation,*.

Sproule-Jones, M. (1993). *Governments at work: Canadian parliamentary federalism and its public policy effects*. University of Toronto Press Toronto.

Vengosh, A. (2003). Salinization and Saline Environments. In *Treatise on Geochemistry* (Vol. 9, pp. 1–35). Elsevier. https://doi.org/10.1016/B0-08-043751-6/09051-4

Walker, B. H. (1992). Biodiversity and Ecological Redundancy. *Biology*, *6*(1), 18–23. Retrieved from https://www.jstor.org/stable/pdf/2385847.pdf

Walker, B., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience , Adaptability and Transformability in Social – ecological Systems. *Ecology and Society*, *9*(2).

Walters, C. (1986). *Adaptive Management of Renewable Resources*. (W. Getz, Ed.) (1st ed.). New York, NY: Macmillan Publishing Company. Retrieved from http://pure.iiasa.ac.at/id/eprint/2752/1/XB-86-702.pdf

Warne, A. (2016). *Purple Loosestrife: Best Management Practices in Ontario*. *Ontario Invasive Species Council*.

Winter, T. C. (1999). Relation of streams, lakes, and wetlands to groundwater flow systems. *Hydrogeology Journal*, *7*(1), 28–45. https://doi.org/10.1007/s100400050178

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[1]Vergne & Durand (2010) recommend that further empirical analysis be done to conclusively demonstrate the existence of path dependent behavior. The author believes that the rule theory established in *Understanding Institutional Diversity* (2005) can provide the framework for creating such a test, and it would be beneficial as supporting evidence in this article. However, this analysis remains to be fully explored.

[2] Resource system attributes are assumed to not be resource systems themselves. While they can have features of an adaptive cycle, like what Holling (2001) ascribes to species, they do not consistently display these qualities, such as in non-living attributes such as soil chemical composition and air quality. While it is possible in this framework to divide and subdivide resource system elements, such divisions may give false ideas about the reach of management decisions and create incorrect causality.

[3] The process by which attributes are given relationship to each other can be self-organized (see Folke et al., 1996), or be intentionally designed to include elements of self-organization as proposed in ecological engineering (see Barrett (1999) for an example of ecological engineering as applied to water systems). Elements of both could in this frame work be possible within an ecosystem, but it is outside the scope of this paper to make a claim about what an appropriate approach might be.

[4] Resource cycles can be conceived as being nested, where one smaller adaptive cycle is within a larger adaptive cycle. However, it should be noted that this analogy may create a misconception that there are clear boundaries that separates one cycle from another. This is not the case, and as it is with many models, the separation between adaptive cycles might lead some to lead to overly broad generalizations.

[5] The characterization of events external to the ecosystem refers to events that the ecosystem plays a role in, such as climate. In this framework it is possible to expand the analysis to wider spatial and temporal scales. However, at those points the number of attributes that would drive resource system and ecosystem functions would be too large for any single management legislation.

[6] The difficulty of separating attributes into different systems may mean that a thorough language about attributes needs to be developed. However, the language here has been deemed adequate for this discussion.

[7]The framework for analyzing resource systems in terms of resource system attributes and adaptive cycles could be used to analyze the choices made between what resource units to maximize, and long-term consequences. However, this other type of path dependent behavior, if it can be called that, lies outside of the scope of this paper.
[8] The brown-headed cowbird is endemic to Texas, but managers have begun to treat it like an invasive due to its effects on songbird populations.
[9]The history of California water rights, while not essential to a basic understanding of the rights system that was created, is worth mentioning here given the nuance it adds to the basic structure of rights in the wider state. Pre-1914 riparian and riparian appropriative rights do not have specific limits on the amount allotted to producers. For all intents and purposes, they are unlimited (Hanemann, Dyckman & Park, 2015). Pre-1914 rights are also considered to be the most senior of rights, meaning that the only solution for a conflict between two pre-1914 rights is adjudication, given that both of their seniority is equal (Hanemann, Dyckman & Park). However, these issues do not have significant impact on Southern California, and have a larger impact in the central part of the state. The one major seniority debate that has occurred within southern California was Los Angeles's senior rights to the Los Angeles River and the waters flowing from the San Fernando Valley to Arroyo Secco (Green, 2007; Blomquist, 1992) from the original mission's rights.